



## Shining a light on the loss of rheophilic fish habitat in lowland rivers as a forgotten consequence of barriers and its implications for management

Birnie-Gauvin, Kim; Aarestrup, Kim; Riis, Torsten M. O. ; Jepsen, Niels; Koed, Anders

*Published in:*  
Aquatic Conservation: Marine and Freshwater Ecosystems

*Link to article, DOI:*  
[10.1002/aqc.2795](https://doi.org/10.1002/aqc.2795)

*Publication date:*  
2017

*Document Version*  
Peer reviewed version

[Link back to DTU Orbit](#)

*Citation (APA):*  
Birnie-Gauvin, K., Aarestrup, K., Riis, T. M. O., Jepsen, N., & Koed, A. (2017). Shining a light on the loss of rheophilic fish habitat in lowland rivers as a forgotten consequence of barriers and its implications for management. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 27(6), 1345-1349. <https://doi.org/10.1002/aqc.2795>

---

### General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46

**Shining a light on the loss of rheophilic fish habitat in lowland rivers as a forgotten consequence of barriers and its implications for management**

*In press in Aquatic Conservation: Marine and Freshwater Ecosystems  
as a Short Communication*

Kim Birnie-Gauvin<sup>1</sup>, Kim Aarestrup<sup>1</sup>, Thorsten M. O. Riis<sup>2</sup>, Niels Jepsen<sup>1</sup>, Anders Koed<sup>1</sup>

<sup>1</sup> DTU AQUA, National Institute of Aquatic Resources, Section for Freshwater Fisheries Ecology, Technical University of Denmark, Vejlsovej 39, 8600 Silkeborg, Denmark

<sup>2</sup> Limfjord Council, Stigsborg Brygge 5, 9400 Nørresundby, Denmark

Author for correspondence: K. Birnie-Gauvin, [kbir@aqu.dtu.dk](mailto:kbir@aqu.dtu.dk)

**Running title:** Habitat loss as a forgotten consequence of barriers

47 **Abstract**

48 1. The majority of rivers around Europe have been modified in one way or another, and no  
49 longer have an original, continuous flow from source to outlet. The presence of weirs and dams  
50 has altered habitats, thus affecting the wildlife that lives within them. This is especially true for  
51 migrating rheophilic fish species, which in addition to safe passage depend on gradient and fast  
52 flowing waters for reproductive success and early development.

53 2. Thus far, research has focused on investigating the impacts of weirs and dams on fish passage,  
54 with less attention paid to the loss of habitat entrained by such infrastructures. The loss of  
55 rheophilic habitat is particularly important in lowland streams, where gradient is limited, and  
56 dams and weirs can be constructed with less effort.

57 3. Denmark is considered a typical lowland country, where the landscape around streams and  
58 rivers has been modified by agriculture and other human activities for centuries, leaving  
59 management practitioners wondering how much change is acceptable to maintain sustainable  
60 fish populations and fisheries practices.

61 4. With examples from Denmark, we attempt to conceptualize the loss in habitat as a result of  
62 barriers in lowland streams and rivers, and the repercussions that such alterations may have on  
63 rheophilic fish populations. Furthermore, we emphasize the need for management to address  
64 habitat loss and its related consequences concurrently with the improvement of fish passage.

65

66 **Keywords:** river, stream, fish, river management, catchment management, indicator species,  
67 hydropower, impoundment

68

69

70 **Introduction**

71 The presence of barriers (such as weirs, dams and culverts) in rivers has grown immensely in the  
72 last centuries. These barriers are most often put in place to serve human needs, such as to  
73 generate electricity (Welcomme, 1995), though fish farming, irrigation and flood control are also  
74 common (Jungwirth, 1998; Jungwirth, Muhar, & Schmutz, 2000). When barriers were first  
75 established, the potential detrimental impacts to the surrounding environment were not  
76 considered (Hunt, 1988), but it quickly became apparent that they had severe consequences to  
77 river ecosystems and the organisms that live within them (e.g., Aarestrup & Koed, 2003;  
78 Alexandre & Almeida, 2010; Dynesius & Nilsson, 1994; Junge, Museth, Hindar, Kraabøl, &  
79 Asbjørn Vøllestad, 2014; Koed, Jepsen, Aarestrup, & Nielsen, 2002).

80 Many countries lack a complete inventory of water barriers and those that do typically  
81 register large barriers only (e.g., the United States National Inventory of Dams for dams above  
82 10m). In Denmark, the Ministry of Environment and Food has recently generated an inventory of  
83 barriers to implement the EC Waterframe Directive (Council of the European Communities,  
84 2000). Although quite comprehensive, even this inventory is unlikely to account for all Danish  
85 barriers given that smaller weirs and especially culverts often remain unregistered. While  
86 freshwater management have remedied some of the negative consequences of barriers associated  
87 with fish passage (e.g., through fish ladders, fish pass etc.), most of the habitat changes due to  
88 damming are still present and thus still threaten stream and river ecosystem sustainability. The  
89 need to take action is pressing given that riverine ecosystems are in the poorest condition of all  
90 ecosystems across the globe (WWF, 2016). To date, there has been tremendous focus on the  
91 impacts of barriers on fish passage (both upstream and downstream movements; e.g., Aarestrup  
92 & Koed, 2003), and finding ways to establish minimal flow to sustain fluvial habitat (Rood et al.,

93 2005). While this approach has merit for management, it ignores some basic problems: (1) it  
94 does not account for the loss of habitat in the resulting “ponded” zone that results from  
95 damming, and (2) it typically ignores the small-scale migrations and movements of less known  
96 species (Larinier, 2001). Moreover, current management schemes tend to neglect effects on other  
97 aquatic organisms, such as plants and invertebrates, which are also affected by the presence of  
98 obstacles (Merritt & Wohl, 2005, Palmer, Arensburger, Botts, Hakenkamp, & Reid, 1995).

99 Here, we briefly describe the important consequences of barriers for rheophilic fish  
100 species (i.e., species that live in fast-moving, oxygen-rich water), with greater focus on (1)  
101 quantity of habitat lost due to a loss in gradient, and (2) lowland streams/ivers given that  
102 gradient is a limiting factor for rheophilic fish reproduction and development in such  
103 watercourses. We attempt to conceptualize the loss in habitat as a result of barriers, and present a  
104 “quick and dirty” method that could be applied to management scenarios which aim to restore  
105 the river continuum and natural habitats for rheophilic fish species.

106

### 107 **Habitat changes as a consequence of barriers**

108 Barriers result in fragmentation and decoupling of hydrological, geomorphological and  
109 ecological aspects of a river, thereby modifying habitat and restricting movement between them  
110 (Lucas & Baras, 2000; McCluney et al., 2014; Nilsson, Reidy, Dynesius, & Revenga, 2005; Poff  
111 et al., 1997; Ward & Stanford, 1983, 1995). Specifically, the upstream section becomes a  
112 “ponded zone” and the length of this zone depends on the height of the dam and the watercourse  
113 gradient (Petts, 1984; Poff et al., 1997; Stanford et al., 1996; Figure 1). In turn, this completely  
114 changes the river habitat upstream of the barrier, such as increasing homogeneity of substrates  
115 and vegetation (Nilsson & Jansson, 1995; Poff, Olden, Merritt, & Pepin, 2007), increasing depth,

116 reducing current speed, reducing oxygenation, causing sedimentation and changing water  
117 temperatures (Petts, 1984; Poff & Hart, 2002). The downstream habitat also becomes altered, but  
118 for the purpose of this paper, we focus primarily on the upstream geomorphological changes  
119 induced by barriers.

120

### 121 **Lowland streams and rivers: case studies from Denmark**

122 In lowland streams, the areas with relatively high gradients are preferentially selected to  
123 construct barriers because of their greater relative potential for energy (Hoffman & Dunham,  
124 2007). Damming effects also vary depending on the size of the watercourse and the location of  
125 the dam. Generally, a dam located closer to the source of a river will have fewer repercussions  
126 than one located further downstream (Figure 1), because the gradient of the river is typically  
127 greater in the upper regions, and therefore a smaller proportion of the watercourse is affected by  
128 the damming. Furthermore, upstream parts of a river tend to be narrower than downstream  
129 sections, thus the total damming impacts are considerably lower when a barrier is upstream  
130 (Figure 1), though may still have important consequences for local species.

131 In Denmark, a country consisting solely of lowland landscapes, rivers are typically small,  
132 and have smaller gradients than those from more mountainous countries. While a river in  
133 Norway, for example, can easily provide a drop of 500m, even the larger Danish rivers typically  
134 begin below 100m above sea level. Large gradients are therefore a limited resource in Denmark.  
135 Nonetheless, much of the wildlife in Danish rivers relies on these scarce habitats (especially  
136 rheophilic fish), making them especially important to protect. Within lowland rivers, the areas  
137 where the gradient is (relatively) large, there is greater potential for harnessing water power,  
138 often leading to the establishment of more than a single dam throughout the river course. For

139 example, River Grejs (Vejle, Denmark) runs for approx. 15km, and has a total drop of 55m from  
140 source to outlet, where a total of 11 dams were established by 1986.

141 An altered flow regime caused by dams affects the wildlife present, typically reducing  
142 biodiversity (Bunn & Arthington, 2002; Power, Dietrich, & Finlay, 1996) and population size of  
143 migratory species (Hubbs & Pigg, 1976; Zhong & Power, 1996). This is especially true for  
144 rheophilic species (Hoffman & Dunham, 2007). Hence, the increase in water level (i.e.,  
145 increased depth) and current decrease may be used as indicators of the loss in geomorphological  
146 variability and thus a river's ability to maintain biodiversity, as well as a rough measure of  
147 potential rheophilic habitat loss. This is important because a relatively large proportion of species  
148 that inhabit freshwater streams require relatively fast flowing and oxygen-rich water with varied  
149 substrate conditions in order to thrive; the most common threat to freshwater species (i.e., fish,  
150 amphibians, reptiles, mammals and birds) is habitat loss and degradation from anthropogenic  
151 activities (Freyhof & Brooks, 2011).

152 Given the extent of dam establishment in some lowland rivers, much of what used to  
153 constitute adequate habitats for these species is no longer available. For example, habitat quality  
154 indicator species in Danish rivers, such as Atlantic salmon (*Salmo salar*) and brown trout (*Salmo*  
155 *trutta*), spawn and grow (during early life stages) in stretches where habitat is typified as riffle  
156 areas with gravel or cobble substrate, with low gradients (Gibson, 1993, Gibson, Bowlby, &  
157 Amiro, 2008). Dammed rivers reduce the availability of such stretches, and have been shown to  
158 reduce overall salmonid populations (Welcomme, 1985).

159 Recognizing the consequences of barriers on freshwater ecosystems has led to the pursuit  
160 of mitigation strategies. For example, some municipal and governmental agencies have put in  
161 place new infrastructures to address environmental concerns (e.g., periodic high flows, fish

162 ladders; Auer, 1996). A common approach is the installation of nature-like fish passes. These  
163 bypasses can be useful in allowing fish to move upstream and downstream of a barrier (e.g.,  
164 Calles & Greenberg 2005) but do not remedy the underlying habitat alterations caused by  
165 barriers (Dadswell, 1996), and have been found to have limited success (Bunt, Castro-Santos, &  
166 Haro, 2012). Recent evidence suggests that dam removal provides an efficient management tool  
167 for ecological restoration of freshwater ecosystems (reviewed in Bednarek, 2001), and should be  
168 considered where possible. In fact, complete dam removal restores habitat quality, quantity *and*  
169 connectivity, thus restoring previously lost habitat (Pess, McHenry, Beechie, & Davies, 2008),  
170 enabling rheophilic fish populations to re-establish and also enabling fish to migrate (both on  
171 small and large scales), regardless of how much knowledge we have on a species.

172

### 173 **Conceptualizing habitat loss: applications for management**

174 In Table 1, we provide data for three Danish rivers that vary in size from 3m to 40m in width and  
175 from 20km to 149km in length. We present the total drop from spring to outlet, the summed drop  
176 resulting from barriers, the total length of the river, and the summed length of the ponded zone.  
177 This data was then used as a rough estimate of vertical and horizontal habitat loss (Table 1). This  
178 specific information was chosen given that it is typically easily accessed and could easily be  
179 applied to management strategies. We acknowledge that the habitat loss may not be proportional  
180 to the loss in gradient (as this approach suggests). In fact, the relationship between habitat loss  
181 and gradient is likely more complex, especially if barriers are present further upstream, but this  
182 approach has merit to rapidly address some of the management concerns we are currently facing.

183         This approach shows that a large proportion of the potential rheophilic habitat is lost in  
184 the ponded zones (Table 1). River Gudena, the longest river in Denmark, was historically one of



185 the most important Danish rivers with large populations of anadromous salmonids. It has seven  
186 barriers in the main stem predominantly for hydro power generation, yielding a total relative loss  
187 of the potential spawning and juvenile development habitat of 36% (Table 1). This loss increases  
188 to approx. 60% if we exclude the upper 10% of the watercourse where the river is narrow, the  
189 gradient is significantly larger, and salmon production is historically non-existent. The smaller  
190 Rivers Villestrup and Omme, on the other hand, have barriers established for fish farming or old  
191 watermill purposes, but nonetheless result in a similar loss in habitat. Furthermore, this estimated  
192 habitat loss is likely underestimated at fish farm sites, because the stretch of the river between a  
193 weir and the outlet of a fish farm is often several hundreds of meters apart, with very little water  
194 flow during a large part for the year. The habitat quality in these stretches is limited as a  
195 consequence of the reduced water flow alone, but may also represent an area of high predation  
196 (Jepsen, Aarestrup, Økland, & Rasmussen, 1998; Poe, Hansel, Vigg, Palmer, & Prendergast,  
197 1991; Ruggerone, 1986).

198         The three rivers discussed in the above paragraph run mainly through agricultural land.  
199 However, rivers running through urban areas may be subjected to even more severe habitat loss  
200 (Birnie-Gauvin, Peiman, Gallagher, de Bruijn, & Cooke 2016). River Mølleaa is approx. 13km  
201 long, and flows through Northern Copenhagen into the Øresund strait. The river has nine dams,  
202 which together remove an estimated 75% of the river gradient. There is virtually no natural  
203 gradient left, and thus no adequate habitat for rheophilic species.

204

## 205 **Conclusions**

206 The productive potential of rheophilic species in lowland freshwater rivers is greatly reduced by  
207 the presence of dams and weirs. Typical management interventions aim to address issues

208 concerning fish passage, but often omit to consider the habitat that has already been lost as a  
209 result of barriers for which we lack empirical data (Abell, 2002). Given the relatively limited  
210 gradient available in Danish rivers (and in lowland rivers across the world in general) and the  
211 potential habitat loss associated with the latter, the overall effects of water barriers on habitat  
212 should be included in assessments of watercourses. These actions should be undertaken  
213 concurrently with the improvement of fish passage and other typical management-related  
214 challenges. To improve the state of regulated lowland rivers may mean that many of these river  
215 obstacles need to be removed in order to reinstate the former gradient and habitat, which may re-  
216 establish proper fauna passage in itself.

217         The purpose of this paper was to shine a light on a problem that is often ignored in  
218 traditional fish management to this day: rheophilic habitat loss resulting from barriers. Too often,  
219 the focus of management is on fish passage alone, ignoring other important effects of damming.  
220 This may be particularly true for lowland rivers. Given the number of dams and weirs in rivers  
221 across the world, we acknowledge that acquiring complete knowledge on habitat loss and fish  
222 passage is a daunting task. However, if the majority of rheophilic-appropriate habitat is lost,  
223 improving fish passage may be pointless. We therefore suggest the use of a “quick and dirty”  
224 method (Table 1) to evaluate the potential loss in habitat as a result of barriers. This approach  
225 may provide managers with an improved overview of the state of rivers, and allow for better  
226 management strategies to be implemented. Further studies should be undertaken to evaluate the  
227 validity of the approach.

228

229 **Acknowledgements**

230 This research was funded by the Danish rod and net fish license funds and the European Union  
231 (AMBER project).

232  
233  
234  
235

## 236 **References**

237

238 Aarestrup, K., & Koed, A. (2003). Survival of migrating sea trout (*Salmo trutta*) and Atlantic  
239 salmon (*Salmo salar*) smolts negotiating weirs in small Danish rivers. *Ecology of Freshwater*  
240 *Fish*, 12, 169-176.

241

242 Abell, R. (2002). Conservation biology for the biodiversity crisis: a freshwater follow-up.  
243 *Conservation Biology*, 16, 1435-1437.

244

245 Alexandre, C. M., & Almeida, P. R. (2010). The impact of small physical obstacles on the  
246 structure of freshwater fish assemblages. *River Research and Applications*, 26, 977-994.

247

248 Auer, N.A. (1996). Response of spawning lake sturgeons to change in hydroelectric facility  
249 operation. *Transactions of the American Fisheries Society*, 125, 66-77.

250

251 Bednarek, A.T. (2001). Undamming rivers: a review of the ecological impacts of dam removal.  
252 *Environmental Management*, 27, 803-814.

253

254 Birnie-Gauvin, K., Peiman, K.S., Gallagher, A.J., de Bruijn, R., & Cooke, S. J. (2016). Sublethal  
255 consequences of urban life for wild vertebrates. *Environmental Reviews*, 24, 416-425.

256

257 Bunn, S. E., & Arthington, A. H. (2002). Basic principles and ecological consequences of altered  
258 flow regimes for aquatic biodiversity. *Environmental management*, 30, 492-507.

259

260 Bunt, C. M., Castro-Santos, T., & Haro, A. (2012). Performance of fish passage structures at  
261 upstream barriers to migration. *River Research and Applications*, 28, 457-478.

262

263 Calles, E. O., & Greenberg, L. A. (2005). Evaluation of nature-like fishways for re-establishing  
264 connectivity in fragmented salmonid populations in the river Emån. *River Research and*  
265 *Applications*, 21, 951-960.

266

267 Council of the European Communities. 2000. Council Directive 2000/60/EC of the European  
268 Parliament and of the Council of 23 October, 2000 establishing a framework for Community  
269 action in the field of water policy. Official Journal of the European Communities L327: 1-73.

270

271 Dadswell, M. J. (1996). *The removal of Edwards Dam, Kennebec River, Maine: its effects on the*  
272 *restoration of anadromous fishes. Draft environmental impact statement, Kennebec River, Maine*  
273 (Appendices 1-3, pp. 92). Nova Scotia, CA: Acadia University.

274  
275 Dynesius, M., & Nilsson, C. (1994). Fragmentation and Flow Regulation of River Systems in.  
276 *Science*, 266, 4.  
277  
278 Freyhof, J., & Brooks, E. (2011). European Red List of Freshwater Fishes. Luxembourg:  
279 Publications Office of the European Union.  
280  
281 Gibson, R. J. (1993). The Atlantic salmon in fresh water: spawning, rearing and production.  
282 *Reviews in Fish Biology and Fisheries*, 3, 39-73.  
283  
284 Gibson, A. J. F., Bowlby, H. D., & Amiro, P. G. (2008). Are wild populations ideally  
285 distributed? Variations in density-dependent habitat use by age class in juvenile Atlantic salmon  
286 (*Salmo salar*). *Canadian Journal of Fisheries and Aquatic Sciences*, 65, 1667-1680.  
287  
288 Hoffman, R., & Dunham, J. (2007). Fish-movement ecology in high-gradient headwater streams:  
289 its relevance to fish passage restoration through stream culvert barriers. Virginia: US Geological  
290 Survey, OFR 2007-1140.  
291  
292 Hubbs, C., & Pigg, J. (1976). The effects of impoundments on threatened fishes of Oklahoma.  
293 *Annals of the Oklahoma Academy of Science*, 5, 133-177.  
294  
295 Hunt, C. (1988). *Down by the river: the impact of federal water projects and policies on*  
296 *biological diversity*. Washington DC: Island Press.  
297  
298 Jepsen, N., Aarestrup, K., Økland, F., & Rasmussen, G. (1998). Survival of radio-tagged Atlantic  
299 salmon (*Salmo salar* L.) and trout (*Salmo trutta* L.) smolts passing a reservoir during seaward  
300 migration. In Lagardere, J. P., Begout Anras, M. L., Claireaux, G. (Eds.), *Advances in*  
301 *Invertebrates and Fish Telemetry* (pp. 347-353), Netherlands: Springer.  
302  
303 Junge, C., Museth, J., Hindar, K., Kraabøl, M., & Asbjørn Vøllestad, L. (2014). Assessing the  
304 consequences of habitat fragmentation for two migratory salmonid fishes. *Aquatic Conservation:*  
305 *Marine and Freshwater Ecosystems*, 24, 297-311.  
306  
307 Jungwirth, M. (1998). River continuum and fish migration – Going beyond the longitudinal river  
308 corridor in understanding ecological integrity. In Jungwirth, M., Schmutz, M. S., & Weiss, S.  
309 (Eds.), *Fish migration and fish bypasses* (pp. 127-145). Oxford: Blackwell Science.  
310  
311 Jungwirth, M., Muhar, S., & Schmutz, S. (2000). Fundamentals of fish ecological integrity and  
312 their relation to the extended serial discontinuity concept. *Hydrobiologia*, 422, 85-97.  
313  
314 Koed, A., Jepsen, N., Aarestrup, K., & Nielsen, C. (2002). Initial mortality of radio-tagged  
315 Atlantic salmon (*Salmo salar* L.) smolts following release downstream of a hydropower station.  
316 *Hydrobiologia*, 483, 31–37.  
317  
318 Larinier, M. (2001). Environmental issues, dams and fish migration. FAO fisheries technical  
319 paper 419 (pp. 45-89). Rome, Italy.

320  
321 Lucas, M. C., & Baras, E. (2000). Methods for studying spatial behaviour of freshwater fishes in  
322 the natural environment. *Fish and Fisheries*, 1, 283-316.  
323  
324 McCluney, K. E., Poff, N. L., Palmer, M. A., Thorp, J. H., Poole, G. C., Williams, B. S.,  
325 Williams, M. R., & Baron, J. S. (2014). Riverine macrosystems ecology: sensitivity, resistance,  
326 and resilience of whole river basins with human alterations. *Frontiers in Ecology and the*  
327 *Environment*, 12, 48-58.  
328  
329 Merritt, D. M., Wohl, E. E. (2005). Plan dispersal along rivers fragmented by dams. *River*  
330 *Research and Applications*, 22, 1-26.  
331  
332 Nilsson, C., & Jansson, R. (1995). Floristic differences between riparian corridors of regulated  
333 and free-flowing boreal rivers. *Regulated Rivers: Research & Management*, 11, 55-66.  
334  
335 Nilsson, C., Reidy, C.A., Dynesius, M., & Revenga, C. (2005). Fragmentation and flow  
336 regulation of the world's large river systems. *Science*, 308, 405-408.  
337  
338 Palmer, M. A., Arensburger, P., Botts, P. S., Hakenkamp, C. C., & Reid, J. W. (1995).  
339 Disturbance and the community structure of stream invertebrates: patch-specific effects and the  
340 role of refugia. *Freshwater Biology*, 34, 343-356.  
341  
342 Pess, G. R., McHenry, M. L., Beechie, T. J., & Davies, J. (2008). Biological impacts of the  
343 Elwha River dams and potential salmonid responses to dam removal. *Northwest Science*, 82, 72-  
344 90.  
345  
346 Petts, G. E. (1984). *Impounded rivers: perspectives for ecological management*. Chichester,  
347 England: John Wiley & Sons.  
348  
349 Poe, T. P., Hansel, H. C., Vigg, S., Palmer, D. E., & Prendergast, L. A. (1991). Feeding of  
350 predaceous fishes on out-migrating juvenile salmonids in John Day Reservoir, Columbia River.  
351 *Transactions of the American Fisheries Society*, 120, 405-420.  
352  
353 Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegard, K. L., Richter, B. D., Sparks, R.  
354 E., & Stromberg, J. C. (1997). The natural flow regime. *Bioscience*, 47, 769-784.  
355  
356 Poff, N. L., & Hart, D. D. (2002). How dams vary and why it matters for the emerging science of  
357 dam removal. *BioScience*, 52, 659-668.  
358  
359 Poff, N. L., Olden, J. D., Merritt, D. M., & Pepin, D. M. (2007). Homogenization of regional  
360 river dynamics by dams and global biodiversity implications. *Proceedings of the National*  
361 *Academy of Sciences*, 104, 5732-5737.  
362  
363 Power, M. E., Dietrich, W. E., & Finlay, J. C. (1996). Dams and downstream aquatic  
364 biodiversity: potential food web consequences of hydrologic and geomorphic change.  
365 *Environmental Management*, 20, 887-895.

366  
367 Rood, S. B., Samuelson, G. M., Braatne, J. H., Gourley, C. R., Hughes, F. M., & Mahoney, J. M.  
368 (2005). Managing river flows to restore floodplain forests. *Frontiers in Ecology and the*  
369 *Environment*, 3, 193-201.  
370  
371 Ruggerone, G. T. (1986). Consumption of migrating juvenile salmonids by gulls foraging below  
372 a Columbia River dam. *Transactions of the American Fisheries Society*, 115, 736-742.  
373  
374 Stanford, J. A., Ward, J. V., Liss, W. J., Frissell, C. A., Williams, R. N., Lichatowich, J. A., &  
375 Coutant, C. C. (1996). A general protocol for restoration of regulated rivers. *Regulated Rivers:*  
376 *Research and Management*, 12, 391-413.  
377  
378 Ward, J. V., & Stanford, J. A. (1983). The serial discontinuity concept of lotic ecosystems.  
379 *Dynamics of lotic ecosystems*, 10, 29-42.  
380  
381 Ward, J. V., & Stanford, J. A. (1995). The serial discontinuity concept: extending the model to  
382 floodplain rivers. *Regulated Rivers: Research & Management*, 10, 159-168.  
383  
384 Welcomme, R. L. (1985). River fisheries. FAO Fisheries Technical Paper 262. Rome, Italy.  
385  
386 Welcomme, R. L. (1995). Relationships between fisheries and integrity of river systems.  
387 *Regulated Rivers: Research and Management*, 11, 121-136.  
388  
389 WWF. (2016). *Living Planet Report 2016: Risk and resilience in a new era*. WWF International,  
390 Gland, Switzerland.  
391  
392 Zhong, Y., & Power, G. (1996). Environmental impacts of hydroelectric projects on fish  
393 resources in China. *Regulated Rivers: Research and Management*, 12, 81-98.  
394  
395  
396  
397  
398  
399  
400  
401  
402  
403  
404  
405  
406  
407  
408  
409  
410

411 **Table 1. Conceptualizing rheophilic habitat loss.** Using three Denmark rivers, the ratio of the  
 412 total drop as a result of barriers (m) to the total drop of the river from source to outlet (m) was  
 413 used as a proxy for vertical habitat loss (%). The ratio of the summed ponded zones (km) to the  
 414 total river length (km) was used as a proxy for horizontal habitat loss (%). This “quick and dirty”  
 415 approach to estimate habitat loss from barriers provides managers with a low cost and effective  
 416 method to get a rapid overview of the current state of freshwater streams and rivers, and may  
 417 enable the implementation of more effective management strategies.

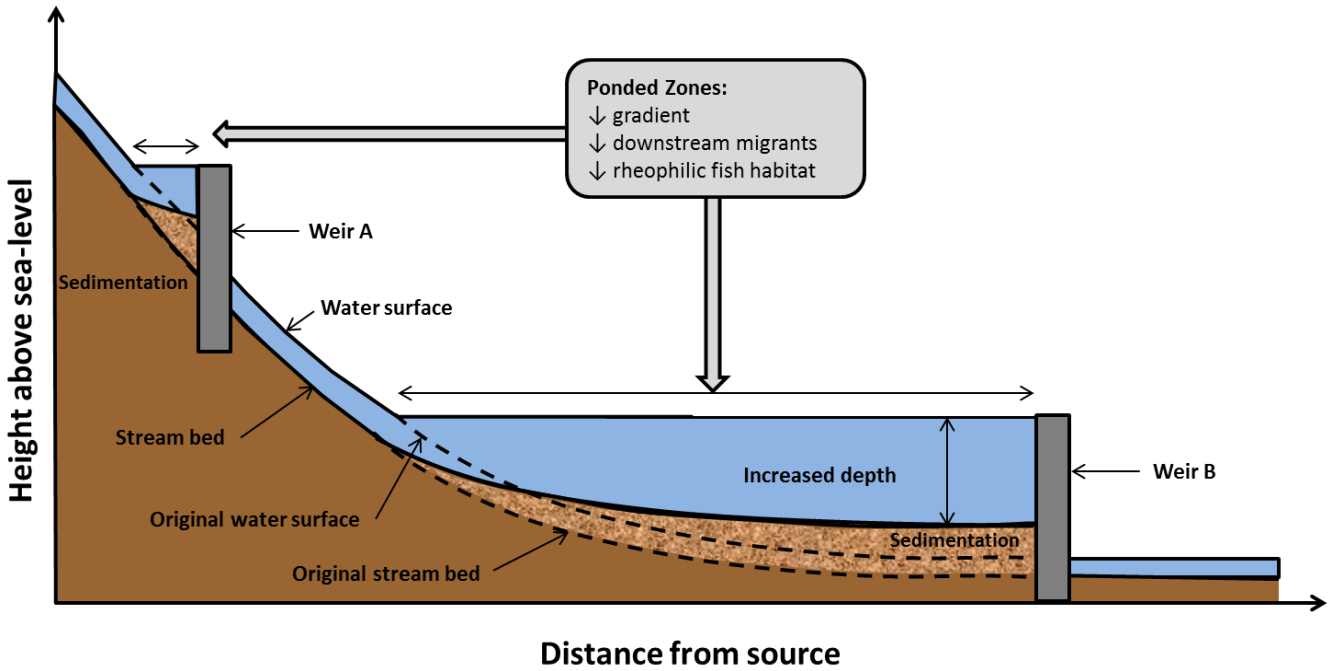
418

<b>River (# of dams)</b>	<b>Total drop from source to outlet (m)</b>	<b>Summed drop from barriers (m)</b>	<b>Vertical habitat loss (%)</b>	<b>Total river length (km)</b>	<b>Summed ponded zones (km)</b>	<b>Horizontal habitat loss (%)</b>
<b>Villestrup (6)</b>	22	8.8	40	20.0	5.8	29
<b>Omme (14)</b>	75	17.7	24	55.0	11.35	21
<b>Gudena (7)</b>	69	24.9	36	149.0	-*	-*

419 \* Information not available given that the weirs and dams are too old to accurately estimate the  
 420 length of ponded zones.

421  
 422  
 423  
 424  
 425  
 426  
 427  
 428  
 429  
 430  
 431  
 432  
 433  
 434  
 435  
 436  
 437  
 438  
 439  
 440  
 441  
 442  
 443  
 444  
 445  
 446

447 **Figure 1. Effects of dams on rivers.** Conceptualized diagram of the effects of dams on rivers  
448 showing two (A and B) identical weirs (i.e., same stemmed height). Depending on the gradient  
449 of the river, the ponded zone differs. As the gradient typically decreases, and the river size  
450 increases, from source to outlet, a similar sized weir closer to the outlet will have a larger ponded  
451 zone, both in terms of length and surface area. Downward-pointing arrows (↓) represent a  
452 decrease.  
453



454